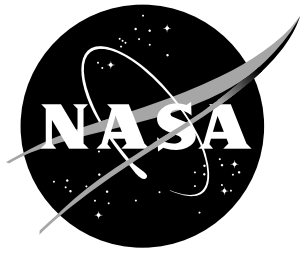


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Wake Vortex Advisory System (WakeVAS) Concept of Operations

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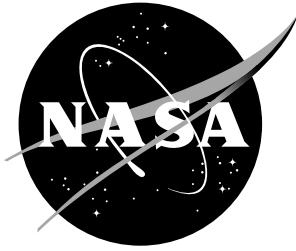
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1.0 Introduction

In response to the growing concern over capacity limitations in the National Airspace System (NAS), research is active on concepts to alleviate constraints via new operational procedures that may include new technologies. A concept for mitigating capacity constraints due to the current method of separating aircraft from wake vortex hazards is described in this report.

1.1 Purpose

NASA LaRC has a rich history of aircraft wake vortex research, with the most recent accomplishment of demonstrating the Aircraft VOrtex Spacing System (AVOSS) at Dallas/Forth Worth International Airport in July 2000. The AVOSS was a concept for an integration of technologies applied to providing dynamic wake-safe reduced spacing for single runway arrivals, as compared to current separation standards applied during instrument approaches. AVOSS included state-of-the-art weather sensors, wake sensors, and a wake behavior prediction algorithm. Using real-time data AVOSS averaged a 6% potential throughput increase over current standards. The AVOSS technologies can be applied to a variety of terminal operations, including single-runway arrivals and departures, intersecting runway arrivals and departures, and operations with Closely-Spaced Parallel Runways (CSPRs).

1.2 Current Operations

Current safe wake vortex separations are achieved with a set of rules for air traffic control and procedures for pilots. The pilot procedures apply any time aircraft are conducting visual approaches and departures. The procedures summarize safe operational practices based on a general understanding of wake behavior. These include taking off prior to the liftoff point of a preceding heavier aircraft; landing beyond the touchdown point of a heavier aircraft; and remaining above the flight path of a heavier aircraft. The rules are based on the general observation that wakes sink when out of ground effect, and tend to separate laterally when in ground effect. Ultimately, the responsibility for wake avoidance lies with the pilot during visual operations.

When instrument approaches are in use, the controller is responsible for applying wake vortex separation standards. The standards are found in the Air Traffic Controller's Handbook [1]. These rules depend on the airport runway configuration and type of operation (arrival or departure). The rules for the airport terminal area are summarized in Table 1.

Table 1 FAA Separation Rules

Type of Terminal Operation	Single Runway or Parallel Runways Less than 2500' Apart	Intersecting Runways
Departures	<p>Behind B757 or heavy- 120 second hold; 180 seconds if intersection or opposite direction same runway</p> <p>OR</p> <p>Radar separation minima</p> <ol style="list-style-type: none"> 1. Heavy behind heavy- 4mi 2. Large/Heavy behind B757 –4mi 3. Small behind B757 – 5mi 4. Large behind heavy – 5mi 5. Small behind heavy – 5mi <p>For pairs not listed the separation is 3 miles</p>	<p>120 seconds behind B757 or heavy departure or landing if projected flight paths will cross; includes parallel runways more than 2500' in separation if will fly through the airborne path of other aircraft</p>
Arrivals	<p>Radar separation minima (at threshold):</p> <ol style="list-style-type: none"> 1. Heavy behind heavy- 4mi 2. Large/Heavy behind B757 –4mi 3. Small behind B757 – 5mi 4. Large behind heavy – 5mi 5. Small behind large – 4mi 6. Small behind heavy – 6mi <p>For pairs not listed the separation is 3 miles, except 2.5 miles in cases when 50 second runway occupancy time is documented and other criteria are met</p> <p>Non-radar minima: 120 seconds for aircraft landing behind an arriving Heavy/B757, except if follower is small then 180 seconds</p>	<p>120 seconds for aircraft arriving after a departing or arriving B757 or heavy if arrival will fly through the airborne path of other aircraft</p>

Also note that for non-radar, timed instrument approaches, the nominal separation is 2 minutes, but it is increased to 3 minutes for small aircraft behind heavy aircraft due to wake concerns. The controller has the responsibility of spacing aircraft such that the separations in Table 1 are maintained. The FAA has the responsibility to ensure that the separations in Table 1 are adequate for wake hazard avoidance. The rules for wake avoidance were determined empirically with experiments such as tower flybys with wingtip smoke generators, and represent the worst-case estimation of wake behavior, which is necessary for any static criteria where safety is of utmost importance. Over the 30+ years of wake vortex research much progress has been made in quantifying the wake behavior as influenced by atmospheric factors such as winds, turbulence and thermal stratification. Wake vortex avoidance rules that are sensitive to the environmental influences on wake behavior could provide more efficient spacing criteria than the worst-case criteria currently used. Research to date indicates substantial capacity improvements can be achieved by reducing wake constraints. See benefits section for details.

1.3 Previous Work

The AVOSS project provided an impetus to advance the state-of-the-art in wake modeling and sensing technology, as well as weather sensing to support predictions of wake behavior. These technologies were integrated to address the single runway arrival radar separation rules. Current weather conditions relevant to wake behavior were sensed and used as a persistence-based forecast to provide inputs to real-time wake prediction algorithms that were valid for a specified time interval. The predicted wake behavior was applied to a region of monitored airspace called the safety corridor, which was a rectangular region centered on the Instrument Landing System (ILS) localizer and glideslope. Wake hazard or residence times in the corridor were used to compute required spacing for wake avoidance. Wakes could cease to be a hazard by 1) sinking below the floor of the safety corridor, 2) being advected laterally from the corridor by crosswinds, or 3) decaying to an intensity below a specified threshold. Real-time wake sensing systems such as pulsed and continuous-wave (CW) Light Detection and Ranging (LIDAR) systems, and wind-lines were used to check the results of the prediction system. A prediction of wake vortex behavior is required in addition to wake sensor observations since spacing recommendations need to have some practical amount of lead-time and be stable for a certain time interval. For detailed descriptions of the AVOSS see refs [2, 3].

2.0 Concept Description

2.1 Overview

NASA Langley has generalized the system configuration demonstrated in AVOSS to a concept for minimizing the impact of aircraft wakes on operations by applying the technologies demonstrated in AVOSS at potentially any airport with any operational configuration. The core enabling components of AVOSS do not depend directly on the operational application to which they are applied, but the overall system configuration must be modified for the airport runway configuration and procedures. The AVOSS technologies produced substantially improved knowledge of wake position and strength as compared to that implied by current wake separation procedures, and this knowledge can be used to maximize efficiency in all airport operations. This can be understood further by considering the common requirements for a system to reduce wake constraints. Figure 1 shows a functional diagram of such a system.

As the flowchart in Figure 1 shows, a region of airspace that will be monitored and assessed for wake hazard must first be defined. In AVOSS, this region was a rectangular region centered on the ILS localizer and glideslope for single-runway approaches. In other applications, it could be a wider “fan” for departures, a cross around the intersection of intersecting runways, or a rectangle around a parallel runway complex. The dimensions of the region will determine the type of sensors used and their performance specifications. Once the region is defined, it can be monitored with active wake sensors and prediction algorithms. When the monitoring shows or predicts a region is free of wake hazard with a certain level of confidence, reduced spacing procedures can be applied. In the upper branch of Figure 1, a technology-independent solution is suggested where current wake knowledge implies a permanent, static change to separation criteria in a limited number of specific operations. An example is the 2500-foot rule, where parallel runways separated by less than 2500’ must be considered a single runway for wake avoidance procedures. It may be possible to relax this requirement to a number less than 2500’ for specific airports because of local predominate meteorological conditions. But the majority of locations and operations are likely to require some kind of active monitoring and dynamic procedure for an overall significant benefit to the NAS. The lower branch of Figure 1 shows this type of system, which requires a safety monitor due to the predictive element of ensuring the protected region is free of wake hazard. The safety monitor would be designed to “catch” instances of actual conditions diverging from the predicted conditions, and would then apply a default or fallback procedure.

Figure 2 shows a top-level diagram of the technological and configuration options for the Wake Vortex Advisory System (WakeVAS) CONcept of OPerationS (CONOPS). The left-most box in the block diagram represents technologies that provide increased knowledge of the wake hazard. In the center are the procedures, rules, and interfaces that utilize this wake knowledge in a procedure that interfaces to the rest of the National Airspace System (NAS). The rightmost graphic represents the specifics of the operation that are addressed by the procedure, or a particular airport's configuration. Several options exist for the concept. The concept could be exclusively a ground tool for controllers; it could be a flight deck tool, or a combination of both. The subsystems could reside totally on the ground, in the air, or a hybrid of the two.

Wake predictions and/or observations could be presented to pilots through a Synthetic Vision System (SVS) [4] or a Cockpit Display of Traffic Information (CDTI), using on board sensors and computation or a data-link to a ground based system. This concept, studied in [5], would place the burden of wake avoidance back on the pilots in all meteorological conditions. This is not a large paradigm shift in terms of wake avoidance procedures since currently under VMC pilots remain clear of a preceding aircraft's wake by adjusting the flight path based on a crude understanding (mental prediction) of wake behavior and assessment of the current weather conditions. The large paradigm shift lies in whether synthetic vision systems allow for the introduction of "Electronic Flight Rules" where pilots see and avoid other aircraft and terrain under IMC using a virtual visual representation of the flight environment.

A time-based inter-arrival spacing tool described in [6] could be used to accurately achieve WakeVAS spacing recommendations. The spacing tool is a flight deck resource that allows pilots to accept precise time intervals as a spacing clearance from a leading aircraft. The tool would reduce variances in spacing produced by current speed-based clearances and improve the benefits realized by the WakeVAS. Wake limitations could also be displayed as part of the information.

Given the previously described range of technology implementations, NASA Langley Research Center is focusing on a hybrid system that interfaces to ground controllers, with an optional flight deck data link to enable wake-vortex hazard information to be communicated to the cockpit. The ground controller uses the system advisories to implement wake-safe separation of traffic. The wake information sent to the cockpit would initially be advisory in nature and could serve to increase the flight crew's Situational Awareness (SA). Future implementations could allow the pilot to maintain safe wake separation based on information supplied by a cockpit display.

2.2 Roles and Responsibilities

In the proposed concept, a WakeVAS provides information to a controller for implementing safe wake spacing through clearances to traffic. The information will be dynamic, with various options for resolution. In the coarse resolution extreme, the system could provide a wakes-no-factor/wakes-factor with expected duration advisory. The controller uses this advisory to implement wake-limited or wakes-no-factor spacing, as prescribed in the current separation standards. The fine resolution implementation will require a controller approach spacing tool, in which the dynamic (aircraft-to-aircraft) safe spacing minimums are applied and possibly transparent to the user. Before WakeVAS can provide safe wake-separation advisories, a formal safety analysis will be required.

The pilot of aircraft equipped to receive and display wake hazard information can use this information for increased SA during visual approaches and departures, when the responsibility of wake avoidance has been transferred from the controller to the pilot. If certain regulatory issues such as the acceptance of electronic flight rules are overcome, the possibility for transferring wake avoidance responsibility to the pilot in IMC can be introduced. Note that the current concept does not depend on the flight deck display of wake information, but includes options to facilitate this interface.

2.3 Architecture

The WakeVAS architecture is shown conceptually in Figure 2. Starting from the left of the figure, data fusing algorithms integrate wake measurements, as well as atmospheric inputs from aircraft, terminal and National Weather Service (NWS) ground sensor systems, and NWS Numerical Weather Prediction (NWP) models. The atmospheric data provides inputs to the wake behavior prediction algorithms that estimate the mean and variance of wake positions and strengths. Aircraft information such as type, speed, and weight are also inputs to the wake prediction algorithms. The observed atmospheric data provides feedback for the training of probabilistic forecast guidance tools derived from NWP models, which are used to estimate how the atmospheric conditions that influence wake behavior will vary over time. Wake sensors monitor the actual wake behavior. The wake and atmospheric observation and prediction subsystems are integrated in a closed-loop system that constantly compares the predictions to observations. The measurements determine divergence in predicted and observed wake behavior. The comparison will contribute feedback to the entire prediction system by 1) providing short term corrections to the predictions, by applying the observed divergences to increase the variance in the wake parameters used to compute wake hazard durations and 2) provide the necessary databases for improving probabilistic wake prediction algorithms [7] and training [8,9] of meteorological model ensembles [10,11] for terminal area NWP. To compute wake hazard durations, the predicted behavior is applied to a region of protected airspace defined for the particular airport operation targeted, and safe spacing intervals between aircraft are derived. A safety monitor function adjusts wake hazard durations appropriately based on the variance in wake and weather parameters reported by the system.

The spacing data becomes an input to a controller tool or interface, the nature of which depends on the resolution of spacing adjustments, as discussed previously. The information can also be up linked to aircraft equipped to use the information in flight deck displays, and Figure 2 shows this link in gray to illustrate its optional status in the CONOPS.

The WakeVAS concept relies on a number of enabling technologies, some of which were demonstrated during the AVOSS project. They are listed as follows, with notes on their maturity level:

1. *Wake Sensors* – The AVOSS utilized pulsed and CW LIDAR [12,13] for measurements of vortex location and strength. A windline [14] was also used for measurements of vortex lateral position. Each sensor system used in AVOSS could be classified as a research sensor, but commercial pulsed LIDARs with wake-measuring capabilities can now be purchased. Detailed performance specifications of even the commercial LIDAR have yet to be determined. In addition, none of the AVOSS sensors could measure both wake position and strength in all weather conditions. Due to this and other limitations research continues on other candidate wake sensors.
2. *Weather Sensors* – AVOSS used a variety of commercial weather sensors to characterize the wake-relevant terminal area ambient conditions. A down-select of the weather sensors used in AVOSS is required to determine the minimum necessary WakeVAS sensor suite. Candidates include an instrumented tower (for low-level wind, temperature, and turbulence measurements), a UHF profiler with a Radio Acoustic Sounding System (RASS) (low to middle level winds and temperature), a pulsed LIDAR (serving the dual task of wake and wind measurement), and aircraft measurements. Aircraft have the potential of measuring all the parameters of interest at a high resolution, under all weather conditions, over the entire region of interest, and thus represent the primary means of collecting weather information. Some corroboration with ground sensors is likely to still be required.
3. *Terminal Weather Predictor* – A WakeVAS will cause dynamic changes to airport departure and arrival rates. In order for affected parts of the NAS to react and take advantage of the changes,

sufficient advance knowledge of the changes will be required. This can be achieved with an accurate terminal-area-scale prediction of the relevant environmental parameters that affect wake behavior. A technology for accomplishing this was demonstrated in the AVOSS project, called the Terminal Area Planetary Boundary Layer Prediction System (TAPPS) [15]. Emerging technologies (e.g. ensemble forecasts) are also under consideration for improving terminal-area-scale NWP [10,11].

4. *Sensor Fusing Algorithms* – Data from a variety of sensors with different resolutions/effective ranges, and operational constraints will have to be integrated into single profiles of winds, temperature, and turbulence. Algorithms for fusing these sensor inputs (the sensor data often disagrees, as discovered during AVOSS) must be developed. These algorithms must include quality control measures so the confidence in the reported parameters can be determined. The AVOSS included a prototype for this function, see references [2] and [3].
5. *Wake Prediction Algorithms* – The real-time wake behavior prediction algorithm used in AVOSS [16] represents the state-of-the-art in a real-time wake model. Despite its sophistication it will not be adequate for an operational system because it does not specify the wake behavior in a probabilistic manner. A mean and variance of the wake position and strength is required along with a confidence measure of those values to perform a formal safety analysis of the system. The wake prediction algorithm should also be integrated with the weather predictions, observations, and wake observations in a closed-loop system that adjusts for predictions diverging from observations. This configuration has not previously been tested.
6. *Aircraft Meteorological Data* – As mentioned in the discussion on weather sensors, aircraft may be the only way to get all the required environmental data over the region of interest. Aircraft already measure and report meteorological parameters, but the resolution of the data is not adequate for a WakeVAS. The feasibility of obtaining the required resolution data from the aircraft systems has been demonstrated, but not in real-time.
7. *Air/Ground Data Link* – The concept requires both meteorological and aircraft state data (e.g. speed, weight) to be communicated to the ground prediction system. The bandwidth of the link is still an open research question.
8. *Controller Tools/Displays* – No controller tool was tested during the AVOSS project. The system was designed, however to interface through a dynamic set of weight-category dependent spacing standards to CTAS. A high-resolution spacing tool such as what is included in CTAS is one option, and at the other spacing resolution extreme is a wake-factor/no-factor with duration advisory, possibly displayed in a similar manner as the ITWS windshear alerts. The controller tool is an open design issue.
9. *Flight Deck Displays* – Similar to the controller tools, no flight deck displays for wake information have been tested; so many issues such as human factors for the design, symbology, coding, alerting and display location remain open research questions. A synthetic vision system is one candidate technology for displaying wake information. Another is a CDTI stand-alone display, or information integrated with the NAV/Guidance/Multifunction display.

The specifications for some of the technologies above will be driven by the performance requirements described in the next section.

3.0 Operational Environment

3.1 Relevant Environment Parameters

The system performance is determined by the behavior of the aircraft wake vortices in the terminal area, and how this performance interacts with and is determined by local procedures, traffic loads, traffic mix, etc. This wake behavior is determined by the type and state (e.g. speed, weight) of the generating aircraft, and the ambient atmospheric conditions. Relevant meteorological parameters affecting wake behavior in the terminal area are ambient temperature, wind, and turbulence. Vertical profiles of these meteorological parameters are necessary in order to predict the wake behavior along the approach and departure paths in and out of the terminal area. The measurement of these parameters feeds the real-time weather and wake prediction systems. Archived databases of these parameters allow for determining diurnal, seasonal, and geographic variability in the terminal area. Mesoscale features, such as frontal zones, outflow boundaries, and low-level jets will impact WakeVAS functionality since these features often go unpredicted or are poorly resolved in NWP models as well as model output statistical (MOS) guidance [7]. Although moisture and air stagnation have negligible affects on wake behavior, they do have an affect on ceiling and visibility, which, in turn, determines if visual approaches can be used or if instrument approaches are required. The aircraft parameters vary by location as a function of an airport's traffic mix. The local procedures constrain how the wake knowledge can be applied to increase the efficiency of operations. For example, the runway configuration determines the region of airspace that must be monitored to ensure safe wake spacing.

3.2 System Performance/Design Parameters

The WakeVAS concept has a number of system design parameters with specifications that depend on the operation targeted. These parameters and some of their proposed values are summarized for the various WakeVAS configurations in Table 2.

Table 2

System Parameter/Type of Operation	<i>Single Runway Arrivals</i>	<i>Single Runway Departures</i>	<i>Parallel Runway Arrivals</i>	<i>Parallel Runway Departures</i>	<i>Intersecting Runway Arrivals</i>	<i>Intersecting Runway Departures</i>
Weather Prediction Interval	30min-2hr	2min-30min	30min-2hr	2min-30min	30min-2hr	2min-30min
Dimensions of Protected Airspace	See Note 1.	See Note 1.	See Note 1.	See Note 1.	See Note 1.	See Note 1.
Operational Weather Minimums	See Note 2.	See Note 2.	See Note 2.	See Note 2.	See Note 2.	See Note 2.
Aircraft Data Link	See Note 3.	See Note 3.	See Note 3.	See Note 3.	See Note 3.	See Note 3.
Error Recovery	See Note 4.	See Note 4.	See Note 4.	See Note 4.	See Note 4.	See Note 4.
Vortex Hazard Metric	See Notes 5, 6	See Notes 5, 6	See Notes 5, 6	See Notes 5, 6	See Notes 5, 6	See Notes 5, 6

Notes

1. The dimensions of the protected airspace depend heavily on the terminal configuration, but in general it should be a region centered on the mean flight path with an n-sigma buffer added. AVOSS was centered on the ILS localizer with a 3-sigma buffer for flight technical error added. Since flight paths are more variable on departures, data must be collected at the installation location to determine the mean flight paths on which to center the airspace region. Due to this added complexity on departures a system that only monitors wake decay may be used for this operation.
2. The weather minimums depend on the requirements the weather and wake sensors must meet. The dimensions of the protected airspace set maximum and minimum range requirements on both sensor systems. If the sensor technology used does not function under certain environmental conditions (i.e. visibility, precipitation) then weather minimums will be relevant.
3. The content of the aircraft to ground data link is known (aircraft type, speed, weight, altitude, ambient temperature, wind speed, wind direction, and Eddy Dissipation Rate) but the bandwidth of the link will depend on the required update interval of the predictions, which depends on whether departures or approaches are targeted. The update interval is also limited by the useful weather prediction horizon.
4. The proposed wake hazard prediction suite will be designed to catch divergences of system predictions from actual conditions and correct for them, which should prevent most cases where a fallback procedure (such as a go-around or ground hold) needs to be applied. These rare-event procedures still need to be designed for the times the event still occurs. The design of these procedures is different depending on the targeted operation.
5. Sensor and prediction accuracy concerning the position of the wake vortex depend on a “proximity hazard metric” that has yet to be defined. The size of the vortex depends on the physical parameters of the aircraft generating it. The size and trajectory of the following aircraft impacts how close to the wake core the follower will be influenced by the wake wind field. Assuming that the probability of a hazardous wake encounter will need to be very low (10^{-9}), the prediction and sensor systems will need to be specified with a probabilistic output so safety assessments can be accomplished for system concepts. Note that the wake hazard metric is a common issue that is not specific to the operation targeted. The type of operation may still determine what aspect of wake behavior (position or strength) is used to define the hazard.
6. Similar to the wake proximity hazard metric described in Note 5, a threshold for a non-hazardous wake strength must be determined and agreed upon by all the stakeholders in the NAS. WakeVAS implementations will not realize their full benefit potential unless wake hazards can be assessed based on circulation strength. Some WakeVAS implementations such as departures may only be able to be realized using wake dissipation as a hazard measure. The AVOSS considered a wake to not be a hazard when its circulation dissipated to a level indistinguishable from background turbulence. The hazard threshold should be dependent on the encountering aircraft size to realize full benefit from the system.

3.3 NAS Interface

The interface of a Wake Vortex Avoidance System (WakeVAS) system into the NAS will be accomplished through the implementation of decision support systems (DSS) and automation tools. These may include approach spacing tools to provide sequencing, spacing, and runway assignment of aircraft on final approach to congested airports; including refined considerations for wake vortex and specific aircraft

characteristic algorithms. Information display techniques will integrate surface, terminal, and wake vortex information into a simplified format to support departing and arriving traffic sequencing. The controller, traffic flow managers, airline operation centers, pilots, and other NAS users will have access to the same DSS and automation tools, which will enable a collaborative decision making capability. Controller-pilot data link communications (CPDLC) service supporting air-ground data exchange used in conjunction with advanced cockpit displays may allow pilots to fly self-separation maneuvers during IFR conditions in the terminal area [17].

4.0 Scenarios

With the architecture and roles and responsibilities defined, this section describes how the “players” in the NAS interact with and use the WakeVAS. A “Day in the life” of the WakeVAS is described for the major terminal operations, describing the sources and flow of information during WakeVAS operation. Key assumptions and changes from current operations are also summarized. Note that the descriptions in this section are notional, with specific assumptions intended to serve as examples only, and not to imply final specifications or requirements.

4.1 Departures

4.1.1 Overview

As stated in Table 1, aircraft departing after a B757 or Heavy category aircraft must be separated with a time-based hold or distance-based radar separation criteria. This separation cannot be waived by the pilot or avoided using divergent departure headings. This separation applies to intersecting runways, when the flight paths of the aircraft operating from each runway could cross.

4.1.2 Significant changes from current operations, procedures, or policies

WakeVAS advisories will allow the separation for aircraft departing behind a B757 or Heavy category aircraft to be waived or reduced as a function of ambient conditions. Ground Controllers will require knowledge of the current departure separations being applied as this could impact sequencing; the Local Controller will also require the information to apply the appropriate minima.

4.1.3 Key Assumptions

The key assumptions for the departure scenarios are as follows:

1. The WakeVAS implementation for the scenarios is not incremental, but a full application of the technologies described in this CONOPS.
2. The responsibility to separate aircraft remains with the ATSP. No flight deck equipment is required to implement the concept.

4.1.4 Description of Concept of Operations

The following scenario assumes a single runway, however, the application of the standards would apply to parallel runway and intersecting runway operations where current procedures require increased separations based on wake vortex considerations.

Airport X is equipped with a WakeVAS configured to monitor single-runway departures. The system (via interface) advises the local controller when ambient conditions are such that wakes are no factor for

spacing¹. The information is conveyed as a separation minimum, and these conditions are predicted to persist for at least the next hour. The Ground Controller issues taxi instruction in accordance with current procedures. Sequencing of departures to optimize departure flows (as opposed to “first come, first served” paradigm) based on pairings may be used. The local controller applies the separation minimum between departing aircraft. This information is broadcast on the ATIS as an advisory that Reduced Wake Vortex Separation Standards (RWVSS) are in effect. In one situation, two aircraft are departing for the same fix, and the departure controller is able to assign divergent courses to transition from the reduced separation minima to the current radar wake vortex separation minima. Another case involves two eastbound departures, and due to terrain constraints divergent flight courses cannot be assigned. Here the local controller must apply the default separation, since the WakeVAS cannot monitor conditions beyond the immediate terminal area.

4.1.5 Mixed equipage operations

Mixed equipage among the aircraft fleet is not applicable to this CONOPS, since flight deck equipment is not required. This may change with future implementations. Airport mixed equipage should also not be an issue, since the WakeVAS will only be used at larger airports that have the necessary infrastructure for a full implementation.

4.1.6 Non-normal operations

Non-normal conditions are characterized by a condition or configuration of the airplane that would not normally be experienced during routine flight operations - usually due to failures [18]. This might include: loss of a required component of a minimum equipment list, electrical failure, display, data link or sensor failures where information is no longer available to the ATSP, or cannot be transmitted to the ATSP for dissemination. When a non-normal failure condition occurs, an assessment of the ability of the aircraft to depart the active runway in a timely manner is determined by communications between pilot and controller. Spacing strategies will be implemented to accommodate the problem if necessary. Potential scenarios include delayed takeoff or departing the runway environment as soon as possible. If taxiing, ground traffic and airport geometries might influence when and where an aircraft can turn off the runway impacting landing aircraft. If the condition results from a ground event, the controller may determine that spacing changes are required of one or more inbound and outbound aircraft until the emergency situation condition is no longer a factor. If the aircraft is disabled and cannot depart the runway, it is assumed that ATSPs will revert to default spacing and/or procedures.

4.1.7 Rare-normal operations

Rare normal is a fault-free condition that is experienced infrequently by the airplane due to significant environmental conditions (e.g., significant wind, turbulence, or icing, etc) [18] or non-routine operating conditions (e.g., out-of-trim due to fuel imbalance, loss of control surface, loss of powerplant, or loss of critical sensor). If an emergency is declared, the aircraft on the runway is disabled or environmental conditions warrant a delay in departures, it is assumed that ATSPs will revert to default emergency handling, spacing and procedures, or implement transition procedures to current default spacing requirements.

¹ For the purposes of this document, the terms “spacing” and “separation” are interchangeable.

4.2 Arrivals

4.2.1 Overview

As summarized in Table 1, aircraft arriving during single-runway operations are subject to minimum separation criteria, which are based on the leader/follower weight categories. For intersecting runways, an arrival or departure on the intersecting runway delays the arrival on the other runway by 120 seconds if the preceding aircraft is in the B757 or Heavy category. Parallel runways less than 2500' apart must be treated as a single runway for the purposes of spacing the arriving aircraft. In general, arrivals have more complications than departures in that the aircraft affected must be managed in the air and delay costs are higher than for aircraft holding on the ground. In addition, aircraft are arriving from a variety of origins so the valid prediction interval for the WakeVAS needs to be large enough to cover the variance in flight times.

4.2.2 Significant changes from current operations, procedures, or policies

The primary difference from current operations for arrivals as with departures is that the static separation rules in Table 1 will serve as an upper limit for dynamic criteria that are output by an advisory system. Since dynamic spacing will result in changing airport arrival and departure rates, information on these rates will need to be predicted and communicated through various levels of the NAS. Assuming that the conditions are such that reduced separation standards can be applied, an AAR that reflects the use of the reduced standards is provided to the appropriate ATC facilities that affect the flow of traffic into the airport. In the event of an anticipated transition from the reduced standards to the traditional "static" standards, the time horizon will dictate the required action to absorb potential delays based from a system standpoint. The system advisories must be conveyed through displays, realized either as new designs or modifications to existing displays. For CSPR procedures, the WakeVAS advisories will be used to determine when paired approaches can be maintained for runways less than 2500' apart.

4.2.3 Key Assumptions

The key assumptions for the arrival scenarios are as follows:

1. The WakeVAS implementation for the scenarios is not incremental, but a full application of the technologies described in this CONOPS.
2. As with departures, the responsibility to separate aircraft remains with the ATSP. No flight deck equipment is required to implement the concept. Technologies that complement the WakeVAS concept will be considered as optional enhancements.

4.2.4 Description of Concept of Operations

Airport X is equipped with a WakeVAS, configured to monitor single runway arrivals. The WakeVAS consists of enhancements to the ITWS that was already present, such as a lidar for real-time wake, wind, and turbulence measurements, data links to aircraft on-board meteorological measurement systems, and weather and wake prediction algorithms. Environmental data collected as part of the WakeVAS installation has quantified the expected wake behavior and system benefit to allow the airport officials to set airport arrival rates, that vary per the season of the year and the time of day. These rates are used by air traffic management personnel to adjust traffic flow rates and also by the airlines operating at Airport X to schedule their operations.

The WakeVAS continually monitors current conditions and makes predictions for wake-safe spacing between specific aircraft (or aircraft weight categories) in the terminal area that are guaranteed valid for at least 30 minutes. Coarser predictions that span multiple hours are used to maintain the validity of the short-term predictions and anticipate significant AAR changes. Reduced wake vortex separations are provided to the approach controller on the radar display or on an adjacent monitor. Separation minima could be provided on the controller's radar display through inclusion in the aircraft's data block or by accessing the data block through "ball tab" (mouse-like device) and keyboard manipulation. A monitor adjacent to the radar display such as the Systems Atlanta Information Display Systems (SAIDS) [19] could also provide separation minima in a table or other suitable form. Knowing this data is valid for the time it will take to land the aircraft, the controller uses it as a guide to issue clearances for minimum wake-safe spacing at the landing threshold. Traffic Management Coordinators ensure that the flow rates for the subject airport/terminal area are commensurate with the established AARs through coordination with the appropriate ATC facilities. Multi-hour predictions that include frontal passage predictions, convective weather, etc. are used to communicate significant deviation of AAR from prior predictions, and this information is sent to the appropriate traffic flow management entities (e.g. Air Traffic Control System Command Center (ATCSCC) and Traffic Management Units (TMUs)).

Aircraft inbound to the airport select the Automated Terminal Information Service (ATIS) broadcast that advertises that RWVSS are in effect when IAPs are in use. (This is beneficial to the flight crew regardless even though they are receiving control instructions from the ground). In the event that Visual Approaches are in use, knowledge that although "standards are not being applied, flight crews can expect that wake vortex is not a consideration in aircraft spacing. One pilot is in a regional jet equipped with a synthetic vision primary flight display. Upon entering the terminal area, the pilot activates the wake hazard regions display feature. Using wake behavior data uploaded from the airport WakeVAS, the display shows the boundaries of the safe flight corridor behind the preceding traffic. The pilot is still accepting a spacing clearance from the approach controller, since Electronic Flight Rules are still not a reality, but the display serves to increase the pilot's situational awareness.

In a differently equipped B-737, the flight crew is advised of the separation that is required behind a designated lead aircraft by the approach controller (using the WakeVAS information.) Entry of this distance to onboard systems, such as an approach spacing tool, generates speed cues that the flight crew follows to achieve the target separation at the threshold. The approach controller continues to monitor and retain responsibility for separation.

Some afternoon thunderstorms begin forming in the terminal area. Since the climate trends have been measured this weather was not a surprise, and the average AAR reflects this. Due to the unpredictable environment in the vicinity of the thunderstorms, the wake vortex spacing applied is no longer reduced from current standards. The change from the reduced standards was made gradually, since multi-hour predictions in the WakeVAS anticipated the convective weather.

Airport X also has a large runway that intersects with the primary runway. Since aircraft arriving on the primary may still be airborne while passing through the airborne flight path of aircraft departing from the intersecting runway, a 120 second delay was required between the departure and arrival if the departing aircraft was in the B757 or heavy category. Since a WakeVAS is in operation, the system displays a 50 second wake hazard time for the intersection region, allowing the controller to apply a substantially reduced time separation to the arriving aircraft.

4.2.5 Mixed equipage operations

Mixed equipage among the aircraft fleet is not applicable to this CONOPS, since flight deck equipment is not required. This may change with future implementations. Airport mixed equipage should also not be as

issue, since the WakeVAS will only be used at larger airports that have the necessary infrastructure for a full implementation.

4.2.6 Non-normal operations

Non-normal conditions are characterized by a condition or configuration of the airplane or ground infrastructure that would not normally be experienced during routine operations usually due to failures [18]. This might include: loss of a required component of a minimum equipment list, electrical failure; display, data link or sensor failures where information is no longer available to the ATSP, or cannot be transmitted to the ATSP for dissemination. If the condition results from an airborne event, an assessment of the urgency of landing is performed through communication between pilot and controller. The pilot will determine if special handling is required and continue based on the ability of the aircraft to maintain spacing requirements. If the condition results from a ground event, the controller may determine whether or not spacing changes are required of one or more inbound and/or outbound aircraft until the condition has been mitigated. If an emergency is declared by the pilot, or a condition on the ground forces a redirection of traffic flow, it is assumed that ATSPs will revert to default spacing and/or procedures.

4.2.7 Rare-normal operations

Rare normal is a fault-free condition that is experienced infrequently by the airplane due to significant environmental conditions (e.g., significant wind, turbulence, or icing, etc) [18] or non-routine operating conditions (e.g., out-of-trim due to fuel imbalance, loss of control surface, loss of powerplant, or loss of critical sensor). Aircraft will be spaced according to information received or the severity of the condition by the ATSP, therefore, when a rare normal failure condition occurs, it is assumed that ATSPs will revert to default emergency handling, spacing and procedures, or implement transition to current default spacing.

5.0 Potential Benefits

5.1 Impacts of System Operation/Safety

Studies have been performed to date [20,21] attempting to quantify the predicted benefit of a WakeVAS implementation to the NAS. The difficulty in deriving an overall benefit of such a system is twofold: 1) The complex inter-relationships between the numerous pieces of the system, and 2) The lack of high resolution meteorological data at the sites of interest.

Since the NAS is a complex system with many dependencies between its elements, changing the performance of one factor (such as airport arrival rate) has an unknown impact on the system as a whole. An increased aircraft arrival rate could cause congestion on the taxiways or at the gates, problems with baggage claim, and increases in ground traffic around an airport. Increases in capacity will likely create issues with noise abatement, which is a highly sensitive issue at some locations. Comprehensive system level simulations that take all of the factors into account will be required to quantify overall impacts and benefits.

A second issue in quantifying WakeVAS benefits is that since the premise of the system operation is to compute wake-safe spacing that is a function of high-resolution local meteorological conditions, this high-resolution data must be collected from all the airports where a WakeVAS will be used. The conditions will vary by time of day, time of year, and geographic location. Studies such as in [20] only use surface wind speed and direction as inputs to a WakeVAS decision model. As was observed in the AVOSS field deployment [30], ignoring a wake behavior factor such as lateral movement or strength in the hazard computation reduces the projected benefit by as much as 50%. The Dallas departure study in [21] is an

example of what can be done for a location where high-resolution meteorological data above ground level was collected for a significant period of time.

5.2 Capacity Gains

Given the complications described in the previous section, benefits analysis to date suggests changes to the wake vortex separation standards will have positive impacts on terminal capacity. In [22] the average 6% potential throughput increase achieved in the Dallas AVOSS demonstration would result in as much as a 40% delay reduction at airports operating near capacity limits, such as Atlanta International Airport. The Massachusetts Institute of Technology's Lincoln Labs benefit study using a simulation of departure operations at Dallas/Ft. Worth projected a yearly savings of five to ten million dollars from reduced delays resulting from reducing wake separations. The potential savings at many closely spaced parallel runway airports that must reduce operations from two to one runway under IMC may be even greater. As discussed in the previous section, not every factor that balances the parameters analyzed in a system as complex as the NAS has been addressed in these studies, and consequently the potential benefit may be reduced because of these factors. Therefore, the WakeVAS concept of operations is designed to be adaptable and able to improve wake-constrained efficiency in a variety of operations.

6.0 Research Issues/Risks

A variety of open research questions remain that prevent completely specifying the CONOPS. They are listed with explanations in the section.

1. *Accuracy/performance of all sensor subsystems* – Where possible, each subsystem's performance should be understood as well as science permits. The science of measures (metrology) should be used to understand subsystem uncertainty. This uncertainty may be represented in a probabilistic manner, such as a confidence probability. This will facilitate system-level trade and safety analysis, and the generation of detailed subsystem specifications.
2. *Development of probabilistic wake predictor* – AVOSS is an engineering algorithm that predicts aircraft wake vortex transport and decay in current and future weather conditions in the terminal area. Though further research could prove beneficial to the continued development and improvement of this algorithm, a statistical wake vortex predictor must be considered (See justification in (1)). Existing wake and meteorological data sets must be expanded to build databases of relevant wake and meteorological parameters necessary for proper statistical representation. With proper databases a number of approaches are available. An existing data-driven prediction tool, presently used in NWS operations, is known as Model Output Statistics (MOS) [7][23]. MOS relates observed weather elements to appropriate predictors via a statistical approach. MOS guidance enhances NWS operations by 1) objectively interpreting NWP model output based on a historical sample, 2) predicting events forced by synoptic-scale systems, 3) correcting for certain systematic NWP model biases, 4) quantifying uncertainty in NWP model forecasts, and 5) accounting for some local effects by incorporating climatic considerations. To develop a MOS product for terminal scale prediction, existing wake and meteorological data sets must be expanded to build the 'climatologies' of relevant wake and meteorological parameters necessary for proper statistical representation. Multivariate analyses, often referred to as multiple linear regression, would incorporate all existing and future observational data to drive the development of the statistical wake predictor [24]. The wake characteristics would be predicted from comparisons of past wake behavior, meteorological model predictions, and real time meteorological and wake sensors. Another approach is to employ parameter estimation of algebraic models to provide a probabilistic predictor. Results of a feasibility study to develop a data-driven statistical vortex predictor using existing wake vortex data are available in [25]. A

more robust method would be to use univariate/multivariate time series analysis to provide predictions without/with prediction error feedback to make an open/closed loop system. One could also use the point vortex equations and random dynamical theory to develop a set of stochastic differential equations. Integration of these equations will provide the evolution of a system of vortices influenced by random effects such as turbulence. In all cases a good database of wake and meteorological data is necessary for predictor development and validation.

3. *Temporal and spatial variation of relevant weather parameters* – These research questions have implications for the weather prediction horizon and the weather sensing requirements. The spatial (horizontal and vertical) variation of the meteorological parameters monitored will determine the required coverage and resolution of the ground and airborne weather sensors. The temporal variation impacts the measurement frequency of the weather sensors and the length of valid prediction intervals. The atmospheric variability around the terminal will be determined from meteorological observational field studies. WakeVAS development would get extra benefit from field studies by providing databases of the relevant meteorological parameters necessary to drive the development of a statistical wake predictor and training of ensemble meteorological models (see 6 below).
4. *Safety analysis and rare event quantification* – Since the proposed system will provide accurate wake hazard advisories it will need to meet a required level of safety through a formal safety analysis. All the non-normal and rare-normal events will need to be identified and analyzed as well.
5. *Wake hazard definition* – As mentioned in the system parameters section, a wake hazard metric needs to be defined for the CONOPS, based both on wake proximity and strength, and it should account for the response and size of encountering aircraft. A good deal of encounter analysis has been done in both the U.S. and Europe, but a technical and political consensus on what constitutes a wake hazard has yet to be agreed upon.
6. *Quantification of weather prediction horizon* – An open research question is the duration in which a terminal-scale weather prediction is valid, and how the confidence in the predictions evolves with time. The WakeVAS will have different NAS-level impacts depending on the amount of lead-time that exists prior to system changes. New model techniques are currently being researched and implemented operationally to predict weather at the highest possible fidelity. A modeling technique under consideration for potential employment into the WakeVAS system is known as ensemble modeling [8,9,10,11]. Ensemble forecasting is using a collection of individual forecasts valid at the same time to determine parameter mean and standard deviation. Observations are used to ‘train’ the ensemble to reduce the standard deviations, and therefore, improve forecast skill in space and time. As observations are obtained, the ensembles are reinitialized with updated weighting functions that improve the forecasts at longer time periods.
7. *Controller/Pilot workloads/Display design* – Many open research issues remain primarily in the human factors area regarding display design and the human interface for the WakeVAS. WakeVAS impacts on a controller’s workload are not currently known, nor the impact wake information in the cockpit has on a pilot’s situational awareness. Future ATSP display representations integrated into scope symbology should be analyzed to assess appropriate coding of information, interpretive quality, display effects and cognitive workload. If controller display is such that the system advisories are transparent, (e.g. aFAST, pFAST) these issues should be minimized.
8. *Data link requirements* – The aircraft-to-ground data link requirements to support the WakeVAS CONOPS need to be quantified. More information will need to be communicated at a higher

frequency than is currently done for aircraft weather data, and links such as ADS-B do not have all the necessary WakeVAS parameters to date.

9. *Lack of high resolution weather data* – One major obstacle in performing cost/benefit studies for a WakeVAS concept is the current lack of the high resolution terminal area weather data needed to project ranges of wake behavior and the associated effectiveness of an active wake spacing system. Furthermore, performance of statistical wake and meteorological prediction models is dependent on the quantity and quality of observed data. Research in obtaining this data from an effective combination of aircraft, field measurements, and weather models is currently active.
10. *NAS impacts* – As mentioned in (6), a WakeVAS will have system-level affects in the NAS, primarily by modulating airport acceptance rates. The impact of such a system is not currently known and will have to be studied via simulation.

7.0 Transition Issues

The WakeVAS concept is consistent with the FAA’s Operational Evolution Plan (OEP) for the NAS [26]. Under the objective “Keep Terminal Throughput Closer to Visual Levels in all Weather Conditions” there are two solutions that depend on wake vortex spacing limitations. These are “Maintain Runway Use in Reduced Visibility”, and “Space Closer to Visual Standards”. Changing the wake vortex separation rules concerning parallel arrivals and departures in Table 1 enables allowing parallel runways to remain independent under reduced weather minimums. Similarly, reduced separation on approach and departure for all runway configurations requires reduced wake spacing rules to support spacing closer to visual operations. WakeVAS concepts are also consistent with the RTCA 2000 NAS Concept of Operations [27]. In Chapter 5, “Arrivals and Departures”, the RTCA document describes automatic exchanges of information between service providers and aircraft to include weather and hazard alerts such as wind shear, microburst, and wake vortex. Specifically, the RTCA document calls for increased pilot situational awareness through the use of CDTI, to be expanded to include wake vortex separation with other traffic. Increased use of FMS approaches is also considered, and real-time weather data links mentioned in the document will enable these approaches to use weather-dependent wake vortex separation criteria. Finally, the RTCA recommends using enhancements in real-time wake turbulence detection and prediction to enable rates achieved for Visual Approaches when Instrument Approaches are in use. These may be realized in part by information provided to the service provider to enable dynamic wake separation rules.

The RTCA’s NAS Concept of Operations document is divided into short (through 2005), mid (2005-2010) and long (2010-2015) term concepts. The RTCA timeframes are consistent with WakeVAS implementation plans, described in a draft FAA/NASA Wake Vortex Research Management Plan (RMP) [28]. The RMP defines short, mid, and long-term milestones that prescribe a phased implementation of wake vortex procedures and technology into the NAS. Short-term milestones focus on data collection to support static procedural changes, where enough understanding of wake behavior can be accumulated to justify a procedure based on knowledge that the wake “never behaves a certain way”. Since wake behavior is dependent on the characteristics of the generating aircraft and the ambient weather conditions, static procedure changes may only be possible in a small number of airports with relatively stable geographic and weather characteristics and other enabling constraints such as a parallel runway configuration. The short-term efforts will create precedents in changing wake separation rules that will facilitate the mid and long term milestones.

Mid-term solutions include procedures that have a dynamic aspect in that they are dependent on some ambient weather condition. The condition could be a climatological categorization of winds, as was done for the Wake Vortex Warning System (WVWS) in Frankfurt, Germany [29]. Another potential system

concept is discussed in [30], where turbulence measure of the atmosphere is used to predict when wakes will dissipate at a rate high enough to not be a spacing factor. Mid-term milestones will enable the first dynamic wake separation procedures, and advance weather sensing capabilities at airports necessary to support the procedures.

The RMP classifies long-term procedures as those that use active, real-time, wake vortex sensing and prediction. This covers the current WakeVAS concept. WakeVAS is considered long-term because it requires the introduction of the most technology that will have to mature to a level at which it can be certified. This concept has the most unanswered research questions. Data collected during the mid and short term efforts can serve the dual purpose of supporting the current effort and providing data for long-term technology development.

Development of high-fidelity technology models for concept simulations will mitigate risk by enabling concept safety analysis and cost/benefit analysis. Field data collection efforts and prototype deployments will be guided by the simulation studies, so operations and locations with the highest potential benefit can be targeted. Several political/policy changes will need to occur to support the CONOPS. Examples are an augmentation to the current wake separation rules to allow for dynamic, system-provided separations, and consensus on a wake hazard metric. More changes will be required, such as the introduction of “Electronic Flight Rules” before wake separation responsibility can be transferred to the pilot. Several NAS infrastructure changes will also be required, such as augmentations to terminal weather suites and aircraft data link message requirements.

8.0 Summary

Current safe wake vortex separations are achieved with a set of rules for air traffic control and procedures for pilots. The rules and procedures are based on the general observation that wakes sink when out of ground effect, and tend to separate laterally when in ground effect. The previous 30 years of wake vortex research have enabled the development of technologies that have been shown feasible to produce a real-time knowledge of wake behavior. The AVOSS project demonstrated the technical capability of real-time wake sensing systems such as pulsed and CW LIDARs, weather and wake prediction systems, and the potential of integrating these subsystems with a procedure that could increase an airport’s capacity. The next step is to take this concept of environmentally reduced wake separation from the technically possible to practical application. The current concept proposes a system to provide wake safe minimum spacing, which is communicated to controllers and used to space aircraft efficiently during instrument operations. The potential for linking the wake hazard information to the cockpit to improve pilot’s situational awareness during visual operations is also recognized. To do this, a plan detailing the required communications, navigation, and surveillance infrastructure as well as defining the operational procedures needs to be developed and implemented. WakeVAS has the potential to dramatically increase the capacity while maintaining at least the current level of safety at many airports, by using the technology available today and in the near future. This report includes open research issues that need to be addressed to achieve an implementation of the concept, and transition issues that affect how this implementation would occur.

9.0 Figures

Figure 1 WakeVAS functional block diagram

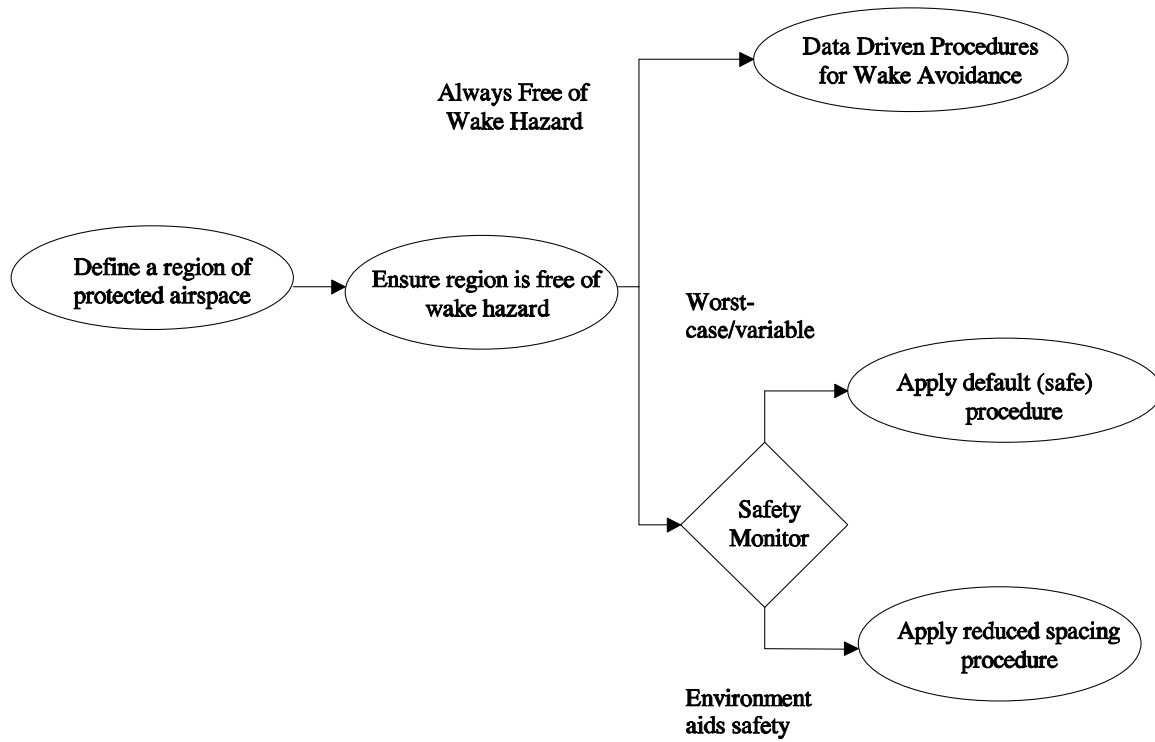
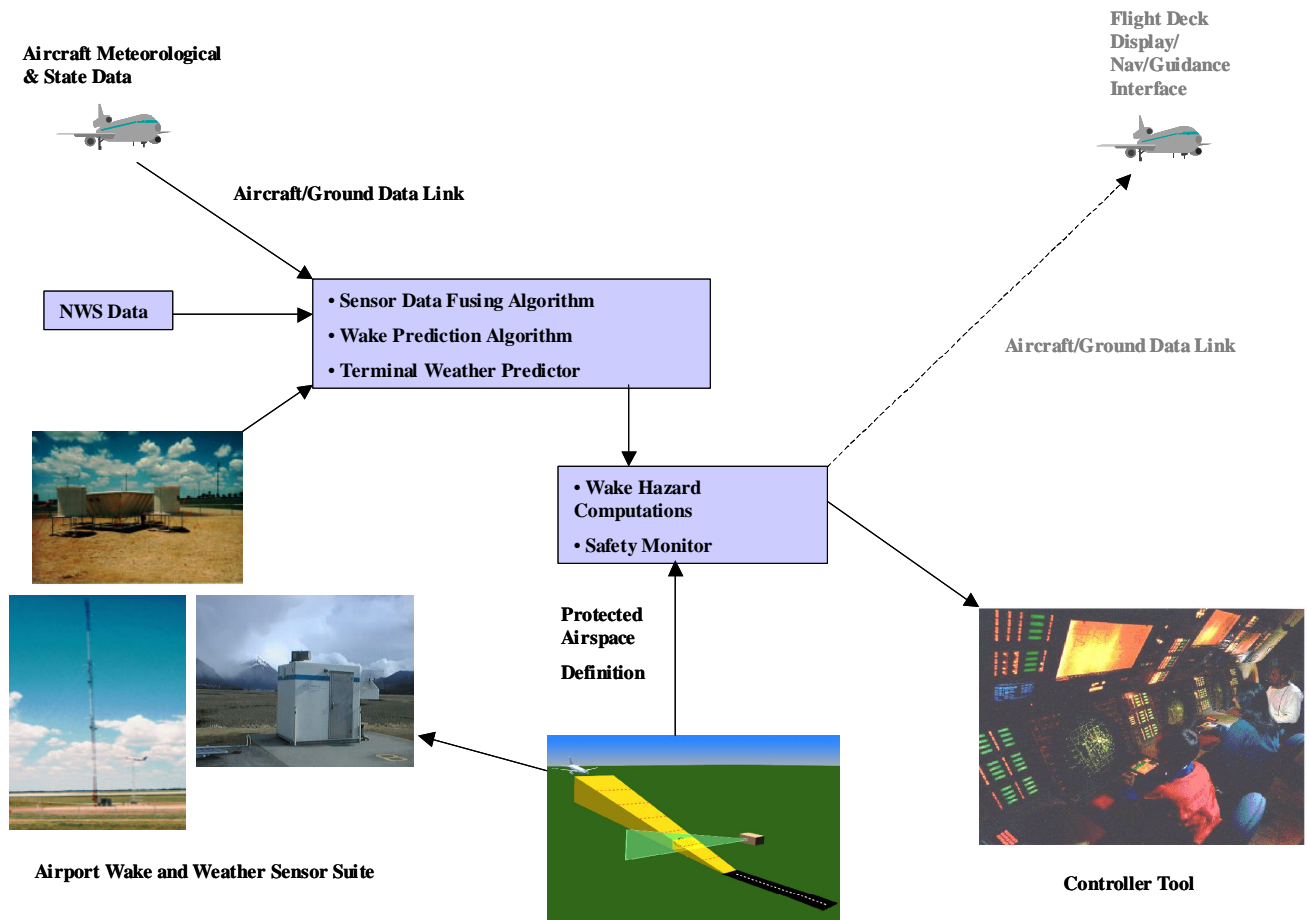


Figure 2 WakeVAS Architecture



10.0 List of Acronyms

AAR	Airport Arrival Rate
ADS-B	Automatic Dependent Surveillance Broadcast
ATC	Air Traffic Control
ATCSCC	Air Traffic Control System Command Center
ATIS	Automated Terminal Information Service
ATSP	Air Traffic Service Provider
AVOSS	Aircraft Vortex Spacing System
CDTI	Cockpit Display of Terminal Information
CONOPS	Concept of Operations
CPDLC	Controller Pilot Data Link Communications
CSPR	Closely Spaced Parallel Runways
CTAS	Center TRACON Automation System
CW	Continuous Wave
DSS	Decision Support System
FAST	Final Approach Spacing Tool
FAA	Federal Aviation Administration
FMS	Flight Management System
IAP	Instrument Approach Procedure
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
ITWS	Integrated Terminal Weather System
LIDAR	Laser Detection and Ranging
MOS	Model Output Statistics
NAS	National Airspace System
NAV	Navigation
NWS	National Weather Service
NWP	Numerical Weather Prediction
OEP	Operational Evolution Plan
RASS	Radio Acoustic Sounding System
RTCA	Radio Technical Commission for Aeronautics
RMP	Research Management Plan
RWVSS	Reduced Wake Vortex Separation Standards
SA	Situational Awareness
SAIDS	Systems Atlanta Information Display System
SVS	Synthetic Vision System
TAPPS	Terminal Area (Planetary Boundary Layer) Prediction System
TRACON	Terminal Radar Approach Control
TMU	Traffic Management Units
UHF	Ultra High Frequency
VMC	Visual Meteorological Conditions
WakeVAS	Wake Vortex Advisory System
WVWS	Wake Vortex Warning System

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